

Anomalous Magnetic Moment of the Muon in a Composite Model

Prasanta Das¹, Santosh Kumar Rai², Sreerup Raychaudhuri³
 Department of Physics, Indian Institute of Technology, Kanpur 208 016, India.
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We make a fresh evaluation of contributions to $(g-2)$ of the muon in the framework of a preonic model with coloured vector-like leptons and heavy coloured Z bosons and discuss their implications in the light of the recent Brookhaven measurement. It is shown that the observed deviation(s) can be accommodated within this framework with masses and couplings consistent with all constraints.

Ever since the original QED derivation of Schwinger[1], the anomalous magnetic moment of the electron — and the muon — has been a testing ground for the correctness of the Standard Model (SM). The most precise measurement of this parameter has been the recent measurement[2]

$$a_\mu = \frac{g-2}{2} = 11\,659\,208\,(6) \times 10^{-10} \quad (1)$$

by the E821 experiment at the Brookhaven National Laboratory (BNL), which is the culmination of a series of measurements of ever-increasing accuracy over the past several years. Given the care and effort which has gone into this measurement, it is probably fair to say that this result is one of the most accurate ever achieved and a triumph of human ingenuity.

The theoretical situation is somewhat more murky. In the SM, the anomalous magnetic moment of the muon arises from electromagnetic, weak and hadronic sources. While there is no problem in determining the first two using the basic electroweak theory, it is not possible to make a perturbative estimate of the hadronic contributions because the strong coupling constant is too large at the muon scale. Accordingly the lowest order vacuum polarisation in the hadronic contribution is calculated using a dispersion integral and the actual data on e^+e^- annihilation to hadrons. With this input, the theoretical prediction is

$$a_\mu^{(e^+e^-)} = 11\,659\,181\,(8) \times 10^{-10} \quad (2)$$

which means that the present measurement (Eqn. 1) deviates from the SM by

$$a_\mu^{\text{exp}} - a_\mu^{(e^+e^-)} = (2.7 \pm 1.0) \times 10^{-9} \quad (3)$$

which represents a 2.7σ excess. On the other hand, the hadronic vacuum polarisation could also be determined by using data from hadronic τ^\pm decays in combination with the CVC hypothesis, and this yields

$$a_\mu^{(\tau^+\tau^-)} = 11\,659\,196\,(8) \times 10^{-10} \quad (4)$$

which is just a little more than 1σ away from the experimental result.

In the normal course of events, one would trust the calculation of $a_\mu^{(e^+e^-)}$ much more than that of $a_\mu^{(\tau^+\tau^-)}$, because the e^+e^- data is much more clean and the number of theoretical assumptions are less. If we accept this, then it appears that the E821 experiment has observed the first real deviation from the SM in experimental data, which makes their result very exciting. This deviation constitutes an immediate challenge to theorists to find possible explanations, and several such analyses have already appeared in the literature. However, since scientists tend to be conservative, the $a_\mu^{(\tau^+\tau^-)}$ calculation cannot and should not be ignored — especially as it is

¹E-mail: pdas@mri.ernet.in

²E-mail: skrai@iitk.ac.in

³E-mail: sreerup@iitk.ac.in

in much better agreement with the SM, which has been tested with spectacular success in so many other areas.

In this article, we shall take the middle ground, *viz.* we shall try to provide an explanation of the nearly 3σ discrepancy between the measured a_μ^{exp} and the calculated $a_\mu^{(e^+e^-)}$ in a model with new physics, but keeping in mind the fact that accepting the $a_\mu^{(\tau^+\tau^-)}$ calculation would provide strong constraints on any such model. It has been pointed out[3] that in order to explain a discrepancy of the observed magnitude in a low-energy phenomenon like the muon anomalous magnetic moment, it is necessary to invoke new physics with particle masses around the electroweak scale as well as couplings of at least electroweak strength. This makes it immediately clear that the new physics responsible for the BNL anomaly cannot be due[4] to effects expected at $\mathcal{O}(1 \text{ TeV})$, such as, for example, graviton exchanges in theories with extra dimensions[5] and possible non-commutative effects in QED[6], which are two of the currently fashionable ideas. On the other hand, supersymmetry, which is the most popular way of going beyond the SM, can explain the observed excess, since it predicts new particles with the correct order of masses and couplings. In fact, several studies have already appeared in the literature[4, 7] which map out the portion of the supersymmetric parameter space which could give rise to the observed effect.

While it is gratifying to know that supersymmetric models constitute an acceptable explanation of the muon anomaly, it is also relevant and interesting to ask what *other* new physics options can give rise to such an effect. Suggestions already made in the literature vary from a scalar leptoquark exchange[8, 9] to lepton flavour-violation[10], exotic vector-like fermions[11], torsion fields in non-Einsteinian gravity models[12] and possible non-perturbative effects at the 1 TeV order[13, 14]. Given the importance of the BNL result, many more suggestions will surely be forthcoming, in the fullness of time.

In this work, we revive earlier ideas[15] that the excess contribution to the muon anomaly could be a signal for compositeness of the muon and of the weak gauge bosons. Given the well-known history of finding layers of substructure every time a significant increase in the resolving power of experiments has increased, it is surely reasonable to address the question whether the BNL anomaly could be the first hint of a new layer of substructure which may be discovered some time in the future. However, it is also a well-known fact that since the original suggestion[16] several – in fact, one may say, dozens — of preonic models have been proposed in the literature. Different models among these have different virtues and various motivations, and it is not our purpose to make a comprehensive survey of these models[17]. A generic feature of all these models, however, is the existence of *excited* leptons and gauge bosons, which are just excited states of the preonic combinations which make up ordinary leptons and gauge bosons. These excitations may be simple orbital excitations, which share the same set of flavour and colour quantum numbers as the SM particles, or they may have exotic flavour and colour charges. To fix our ideas, we concentrate on a well-known model, namely the so-called *haplon* model of Fritzsch and Mandelbaum[18], which has the prime virtues of simplicity and elegance⁴.

The haplon model is based on the assumption that the leptons, quarks and weak gauge bosons of the SM (as also possible neutral and charged scalars) are not elementary particles, but are composed of pairs of preons called *haplons*. The fundamental symmetry of Nature is $SU(3)_c \times U(1)_{em} \times SU(N)_h$, which, of course, makes the photon and the gluons fundamental particles. The weak interaction is no longer a gauge interaction, but is interpreted in this scenario as a feeble van der Waals-type effect of the preonic gauge interaction $SU(N)_h$ (A variant with just a $U(1)_h$ instead of $SU(N)_h$ has also been proposed; however, it is hard to see how this could lead to preon confinement.) In this scenario, the weak isospin and hypercharge have a status similar to the isospin and hypercharge of the meson and baryon multiplets. The haplon model

⁴Another popular model is the *rishon* model of Harari and Seiberg[19]. This has a simpler preonic spectrum than the haplon model, but by virtue of combining together several preons at a time it predicts many more exotic colour states.

is, in many ways, a copy of the quark model at a deeper level, with $SU(3)_c \times U(1)_{em}$ replacing $U(1)_{em}$ and $SU(N)_h$ for the preonic interactions replacing $SU(3)_c$ for the quark interactions. The basic building blocks of matter, then, apart from the photon and gluon, are two fermionic preons $\alpha(\mathbf{3}, -\frac{1}{2}, \mathbf{N})$ and $\beta(\mathbf{3}, \frac{1}{2}, \mathbf{N})$, and two scalar preons $x(\mathbf{3}, -\frac{1}{6}, \bar{\mathbf{N}})$ and $y(\bar{\mathbf{3}}, \frac{1}{2}, \bar{\mathbf{N}})$. Using these, we can build up the entire SM by taking bound states of pairs of haplons, and interpret the three observed fermion families as representing orbital excitations of these bound states. Since it is known that sequential or mirror fermions other than these three families are ruled out by precision electroweak data[20], any further families must be vector-like in nature. The cause for these being vector-like, whereas the first three states are sequential, must be attributed to the dynamics of the bound state, which are as yet unknown.

A natural consequence of having bound pairs of particles belonging to either $\mathbf{3}$ or $\bar{\mathbf{3}}$ of $SU(3)_c$, is to predict the existence of exotic particles such as

- Colour-octet W^\pm bosons ($W_8^\pm = \bar{\alpha}\beta$ in a spin-1 state);
- Colour-octet Z bosons ($Z_8 = \frac{1}{\sqrt{2}}(\alpha\bar{\alpha} + \beta\bar{\beta})$ in a spin-1 state);
- Colour-octet neutral scalars ($H_8 = \frac{1}{2}(\alpha\bar{\alpha} + \beta\bar{\beta} + x\bar{x} + y\bar{y})$ in a spin-0 state);
- Colour singlet and octet charged scalars ($H_8^\pm = \bar{\alpha}\beta$ in a spin-0 state);
- Colour singlet and octet leptoquarks ($\Phi^{+2/3} = \bar{x}y$);
- Colour sextet quarks ($u_6 = \bar{\alpha}\bar{x}$, $d_6 = \bar{\beta}\bar{x}$);
- Colour-octet leptons ($\ell_8^- = \bar{\beta}\bar{y}$, $\nu_{\ell 8} = \alpha y$).

Since such exotic coloured objects would be produced copiously at hadron colliders, it is clear from their non-observation that they must be rather heavy. In fact, direct searches for the coloured fermions leads to the following bounds[20]: $m_{q_6} > 84$ GeV, $m_{\ell_8} > 86$ GeV and $m_{\nu_8} > 110$ GeV. It is also clear from the non-observation of deviations from the SM predictions at hadron colliders that coloured W_8 and Z_8 bosons, as well as scalar leptoquarks (coloured or otherwise) must be rather heavy, with masses typically of the order of a few hundred GeV or a few TeV. Direct detection of such objects — if they exist — may, therefore, have to await the commissioning of the LHC. However, the a_μ measurement at BNL may just provide a window into this mass regime through virtual effects, and this is the motivation of the present work.

We address the question as to whether the existence of so many exotic particles can affect the anomalous magnetic moment of the muon[15]. It may be noted that the current deviation from the SM is typically an effect of the order of 10^{-9} , which makes it comparable to relativistic effects in everyday life. It is interesting to speculate that just as the tiny effect observed (or not observed) by Michelson was the first harbinger of relativity, so the tiny discrepancy observed at BNL could be the first indication of substructure. To this end we have considered the possible contributions to an excess muon magnetic moment from one-loop diagrams involving the *exotic* particle spectrum. Of these, the ones which are of greatest interest are of the following three types:

1. Vertex-type diagrams with a W_8^\pm and/or a H^\pm/H_8^\pm together with a neutrino (coloured or ordinary, as the case may be) in the loop;
2. Vertex-type diagrams with a Z_8^0 and/or a H^0/H_8^0 together with a muon (coloured or ordinary, as the case may be) in the loop;
3. Vertex-type diagrams with a scalar leptoquark $\Phi^{\pm 2/3}$ or $\Phi_8^{\pm 2/3}$ and a quark (ordinary or colour sextet) in the loop.

These follow the topology illustrated in Fig. 1(ii).

In this work, we assume that the interactions of scalar bosons, coloured or otherwise, mimic those of the SM Higgs bosons, *i.e.* these scalars couple to particles with a strength proportional to the particle mass. As a result, their coupling to muons is very feeble and hence the effects of these scalars need not be considered any further. The situation is different for scalar leptoquarks, whose couplings have no SM analogy. While there are strong restrictions on the masses and couplings of scalar leptoquarks from the Fermilab Tevatron data[20], it has nevertheless been shown[8, 9] that scalar leptoquark exchanges can produce the desired excess in $(g - 2)$ of the muon. In this work, however, we exclude this interesting possibility. We also assume that the $SU(N)_h$ scale is very high — too high for any appreciable magnetic moment to arise *directly* from orbital excitations of the preons[13]. Both of these possibilities have already been explored in the literature. We are thus concentrating on the remaining one out of three different ways in which an excess muon magnetic moment can be generated in a composite model.

The detailed Feynman rules for the vector boson interactions in the haplon model are given in Ref. [21]. An interesting feature of these is that the interactions of the W_8^\pm are chiral, whereas those of the Z_8 are vector-like. It is also worth noting that there is no mixing between the Z_8 and the photon, for obvious reasons, and hence, there is no analogue of the Weinberg angle in Z_8 interactions. The fact that the Z_8 interactions are vector-like allows us to evade any constraints from the electroweak precision data, provided we allow the colour octet muon to be practically degenerate with its coloured neutrino partner[20].

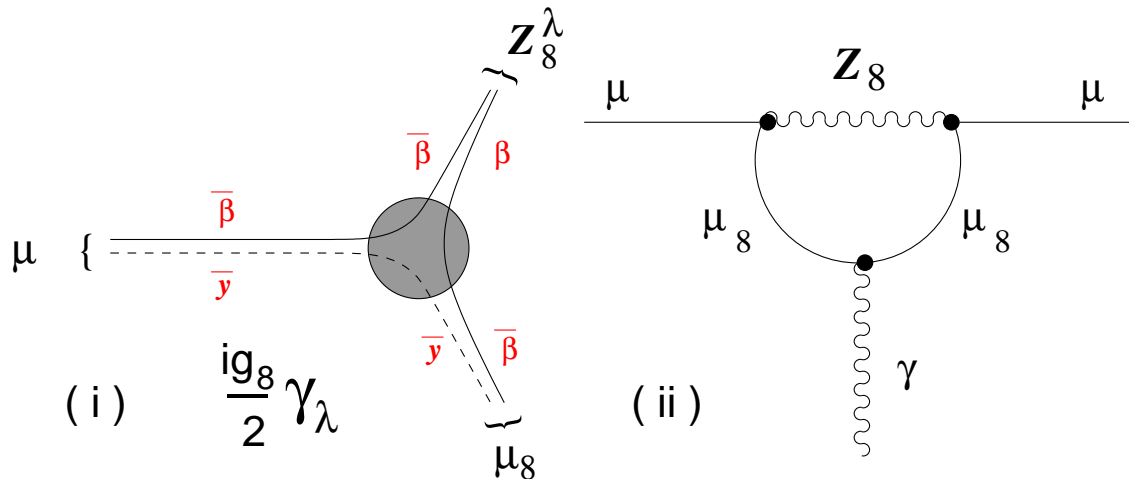


Figure 1. Illustrating (i) the preonic level diagram responsible for the μ - μ_8 - Z_8 vertex $\frac{ig_8}{2}\gamma_\lambda$, and (ii) the corresponding one-loop diagram contributing to $(g - 2)$ of the muon.

It is well-known[3] that chiral interactions lead to contributions to the muon anomalous magnetic moment which are strongly suppressed by the ratio of muon mass to the (large) scale of the new physics, and hence, it is not useful to consider the first type of diagram listed above. On the other hand, it is indeed possible to evaluate the new physics contribution to the anomalous magnetic moment of the muon at the one-loop level using the vector-like Z_8 - μ_8^\pm - μ^\mp interaction illustrated in Fig. 1. It is worth noting that the coupling constant g_8 — again arising from preon dynamics — is unknown but is expected to be of electroweak strength, just like the well-known Z - μ^+ - μ^- coupling. We have two more unknown quantities to consider in Fig. 1, viz. the mass m_8 of the octet muon (μ_8), and the mass M_8 of the octet Z -boson (Z_8). These are expected to be at least a few hundred GeV and may well be much larger.

At this point, it is relevant to ask if there are analogous contributions to the self-energy of the muon and the answer is, obviously, yes. In fact, the muon mass receives large contributions

from all of the above Green's functions, if one simply removes the photon leg. Consequently, the haplon model, like many others of its kind, must be severely constrained by the experimental data on the muon mass[3]. There are two possibilities:

1. The coupling of colour octet W_8 and Z_8 (and leptoquark) bosons to the muon and its colour octet counterpart could be very small ($< 10^{-4}$), and consequently, all contributions to the self-energy would be severely suppressed.
2. The relevant couplings could be large (~ 0.1), but the (large) contributions to the muon self-energy from diagrams with Z_8 - μ_8 exchange and W_8 - ν_8 exchange could cancel to give the correct order of magnitude. Phenomenologically, this can always be arranged by tuning the masses and couplings of the colour octet particles suitably.

It is important to note that *both* these cases involve some fine-tuning. There is no *a priori* reason to assume that van der Waals-type interactions will be suppressed when some of the particles are colour octets — which makes small ($\sim 10^{-4}$) couplings unnatural; at the same time, there is no symmetry which guarantees the cancellation of self-energy contributions of different diagrams to give a net contribution two to three orders smaller than either contribution. However, one of the two mechanisms *must* be at work, since, after all, the muon mass measurements do not allow large self-energy contributions. Of course, the reason must ultimately be sought in the non-perturbative preon dynamics. As these are, at present, unknown, we must work within a set of phenomenological assumptions.

In the first of the above cases, of course, the colour octet bosons and fermions are essentially decoupled from the SM fermions and hence, contributions to the muon anomalous magnetic moment are as severely suppressed as the self-energy. The haplon model cannot then constitute an explanation for the BNL anomaly and hence, the story ends at this point. However, the second option is more interesting, since the chiral structure of the W_8^\pm - ν_8 - μ^\mp and Z_8 - μ_8^\pm - μ^\mp couplings guarantee that there will be near-vanishing contributions to the muon anomalous magnetic moment from diagrams with W_8 - ν_8 loops. Thus, we have a very convenient situation: the W_8 - ν_8 loops cancel the self-energy contribution of the Z_8 - μ_8 loops, *but hardly affect the corresponding contribution to $g - 2$ of the muon*. This is a rare and satisfying situation in beyond-SM physics and can ultimately be traced to the chiral structure of the couplings[3] — itself a consequence of the colour assignments of the extra gauge bosons.

We have not exhibited a detailed analysis of the self-energy contributions since these depend on several unknown parameters, viz., the masses of the W_8 and Z_8 bosons, the masses of the coloured leptons μ_8 and ν_8 (which have to be nearly degenerate to avoid constraints from electroweak precision tests) and the magnitudes of the W_8 - ν_8 - μ and Z_8 - μ_8 - μ coupling constants. All that we require is a sufficiently sensitive cancellation and we have checked that, even keeping the couplings and boson masses of the same order in magnitude, enough leeway remains in the parameter space to arrange for a phenomenological cancellation of the self-energy corrections. It follows that the self-energy yields no useful constraints on the parameters responsible for the muon anomaly.

The contribution of a heavy fermion and a heavy neutral vector boson to the anomalous magnetic moment of the muon has been evaluated several times before[22], and we skip the details of the actual derivation. The one-loop-corrected vertex function of the muon can be written

$$\Gamma_\alpha = F_1(q^2)\gamma_\alpha + \frac{i}{2m_\mu}F_2(q^2)\sigma_{\alpha\beta}q^\beta \quad (5)$$

from which it follows that

$$a_\mu = \frac{g - 2}{2} = F_2(q^2)\Big|_{q^2 \rightarrow 0} . \quad (6)$$

Direct evaluation[22] of the form factor $F_2(q^2)$ using the Feynman rule of Fig. 1 and taking account of the colour factor of 8 leads to the result (in terms of the unknown parameters

g_8, m_8, M_8)

$$a_\mu(Z_8) = \left(\frac{\alpha_8}{2\pi}\right) \left(\frac{m_\mu}{M_8}\right) \frac{\sqrt{x_8}}{(1-x_8)^4} \left[4 - 7x_8 + 3x_8^2 - x_8^3 + x_8^4 + 6x_8(1-x_8)\log x_8 \right. \\ \left. + \frac{1}{12} \frac{m_\mu}{M_8} \frac{1}{\sqrt{x_8}} \left(8 - 38x_8 + 39x_8^2 - 14x_8^4 + 5 - 18x_8^2 \log x_8 \right) \right],$$

where $\alpha_8 = g_8^2/4\pi$ and $x_8 = m_8^2/M_8^2$. For large values of M_8 and $m_8 > 100$ GeV, the terms on the last line of the above equation may be safely neglected.

We are now in a position to make a phenomenological analysis of the haplon model vis-à-vis the E821 data. Our numerical results are set out in Fig. 2. In the left box we have plotted, for three different choices of α_8 ($= 0.1, 0.01, 0.001$), the region in the M_8 – m_8 plane which can explain the BNL 2.7σ excess which arises using the estimate based on e^+e^- data. The darker-shaded regions correspond to the data with errors at the 1σ level, while the lighter-shaded regions correspond to the 2σ level. It is of great interest to note that large values of the exotic particle masses m_8 and M_8 can actually yield the correct order of magnitude of the anomalous magnetic moment. This is because the actual contribution depends only on the ratio of a function of x_8 with M_8 .

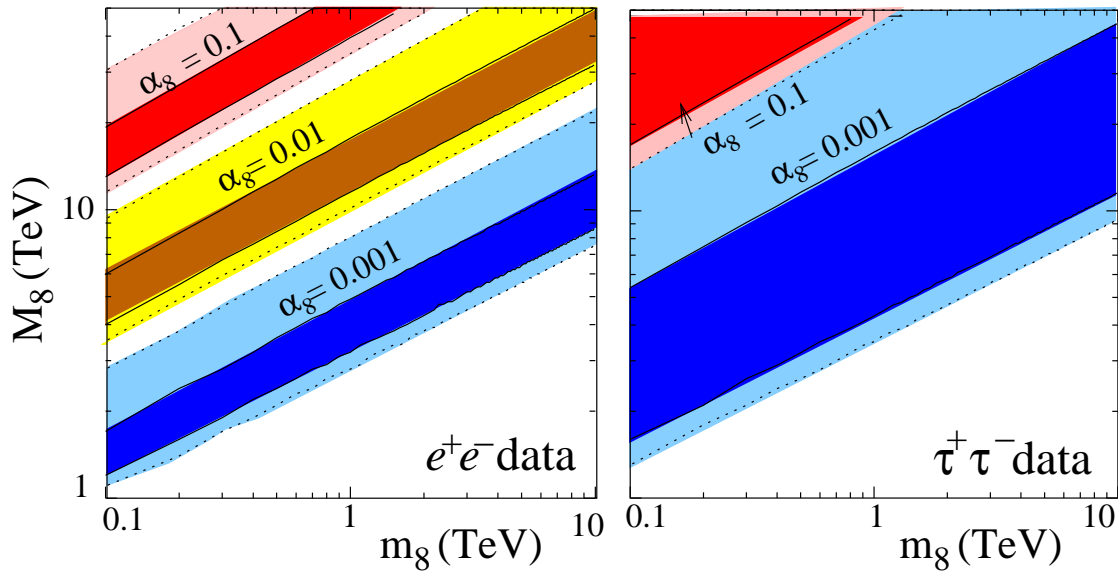


Figure 2. Illustrating the regions in the $M_8 - m_8$ plane which can explain the BNL data. Values of α_8 are marked inside the relevant shaded region. Dark (light) shading denotes the allowed region at $1(2)\sigma$. There is no upper bound on M_8 at the 3σ level because the observed deviation from the SM is at 2.7σ . For the $\tau^+\tau^-$ data, almost all large values of M_8, m_8 are allowed; hence the choice $\alpha_8 = 0.01$ has not been exhibited.

We see, therefore, that it is possible to interpret the observed deviation of the muon anomalous moment from the SM prediction as a signal for a preonic structure of the weak gauge bosons provided the effective coupling α_8 lies in the range 0.001 to 0.1 and other parameters of the model guarantee sufficiently small corrections to the muon mass. The lower value of α_8 represents a superweak-type interaction, while the upper value represents a strong interaction. However, it is gratifying to note that the most favourable region in the parameter space is indeed when α_8 is close to the weak coupling strength, *i.e.* $\mathcal{O}(0.01)$. This value is an eminently desirable feature, given the philosophy adopted in the haplon model. In fact, several interesting phenomenological features of the model emerge. For example, the exotic particle masses which can explain the BNL result are rather large and can easily evade any constraints coming from Fermilab Tevatron data. In fact, to see any manifestation of these exotic particles and their interactions at low energies will generically require a measurement which is precise to the same level as the E821

experiment, which would explain why the observed excess in the muon anomalous magnetic moment could be a single isolated hint of a composite structure of leptons and weak bosons. However, we must note that the coloured Z and coloured muon states cannot be decoupled, i.e. the masses cannot be arbitrarily heavy. Thus, a future experiment which would scan the 10–50 TeV range might actually produce these particles directly.

As we have noted before, it is also necessary to take into account the possibility that the correct theoretical estimate is the one obtained from the τ^\pm data and hence that the BNL measurement is more or less consistent with the SM prediction. In this case, the measurement can only be used to constrain the haplon model. We have plotted the allowed region in Fig. 2 in the box on the right, for two extreme values α_8 ($= 0.1, 0.001$). As expected, the experimental result forces the μ_8 and the Z_8 to be rather heavy — in fact, the Z_8 must be over 1 TeV even when the coupling α_8 is rather small. However, once this is taken, most of the parameter space is allowed, which is consistent with a decoupling behaviour, and is obviously, less exciting.

To summarize, then, we have made a phenomenological analysis of the recent BNL measurement and shown how the possible 2.7σ excess can be interpreted as a signal for heavy exotic coloured lepton and Z -boson states arising in a preonic model. Though, admittedly, this is not a unique way in which the observed deviation from the SM can be interpreted, nor is the haplon model the only preonic model, but our result is nevertheless exciting, since it means that the old idea of substructure remains one of the new physics options which remain viable in the post-BNL scenario. This does not depend very crucially on our choice of model (the haplon model was essentially chosen for simplicity) but it requires a degree of fine-tuning in the muon self-energy whatever be the model chosen. Whether this explanation is the correct one, or whether the postulated substructure is anywhere near the correct theory is something only time and new data from other processes can indicate.

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